Spray Enhancement of ACC Performance at Crockett Cogeneration Plant

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ABSTRACT

Air-cooled condensers are sometimes limited in their ability to maintain desired turbine backpressures during the hottest periods of the year. Inlet spray cooling is a potential approach to mitigating this problem. This paper presents the results from two recently-completed projects.

Field tests were run on one of the auxiliary cooling cells on the air-cooled condenser/ auxiliary heat exchanger at the Crockett Cogeneration plant. Sprays were mounted on a movable rack hung below the fan. Tests were carried out to establish the effect of droplet size (as affected by nozzle choice and nozzle supply pressure), droplet residence time, ambient conditions, spray flow rate and nozzle location on the inlet cooling effect and the efficiency of water utilization.

Cooling effects of 65% to 75% of the wet bulb depression were readily achieved. At the most favorable (hot, low humidity) ambient conditions, water utilization efficiency, (defined as the percent of water sprayed which evaporated in the inlet air stream) approached 90%. A satisfactory performance correlation was developed for the data over all test conditions.

A spray system was designed and installed by Crockett Cogeneration personnel to achieve backpressure reductions on the hottest days. The nozzles were installed inside the A-frame cells above the fans. The system design was based on performance correlations from the previous study and on some flow visualization experiments conducted to minimize wetting of the finned tube bundles with unevaporated spray. Performance data showing the effect on inlet spraying on turbine backpressure during periods of high ambient temperature are presented and are consistent with the correlations developed from the earlier single cell tests.

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Introduction

The use of spray inlet cooling to mitigate the performance reduction incurred by air-cooled condensers on the hottest days of operation has been considered for many years (Conradie and Kroeger). Additionally, a number of installations have installed such systems and experimented with them; some have operated with them over a period of many years. Examples include Chinese Station, El Dorado Energy Center, Braintree, Linden and many others. Results have been mixed particularly with regard to the efficiency of water use and the effect of unevaporated liquid impingement on the finned tube surfaces.

In 2001, the California Energy Commission and EPRI funded a systematic field test of spray enhancement at the Crockett Co-Generation Plant in Crockett, California. Tests were run on a singe cell of the air-cooled exchanger, a three cell auxiliary cooler integrated with the 12-cell air-cooled condenser at the site. Measurements of cooling effect and cell heat transfer improvement were made for a range of nozzle types, droplet size distributions, spray pressure and flow rate and nozzle location during periods of different ambient temperature and humidity over a two month period.

In 2003, Crockett management decided to install full-scale spray enhancement capability on the 12 condensing cells to ensure that full output could be achieved during the hottest hours of the year even if the co-generation host was not accepting the normal steam load. To simplify the system installation and to minimize its cost, the decision was made to install the spray nozzles inside the cells above the fans where they could be easily attached to the fan bridge structure. To help select the preferred nozzle locations and orientation, flow visualization tests were run to see how the spray was transported and dispersed in the air currents inside the cells.

The spray system was operated for just one day during August, 2004 when the ambient temperature was high and the plant output was limited by increased turbine backpressure. Data were taken on that day and compared with performance predictions developed in the 2001 test program. The remainder of this paper summarizes the single cell test results, discusses the findings of the flow visualization tests and presents the data from the full-scale system operation.

Single cell tests---September/October, 2001

The results of the single cell tests have been reported in detail in a CEC/EPRI report (CEC Website) and in two Conference Proceedings (IAHR; EPRI Charleston). They are summarized here for convenience of reference.

Test site

Field tests were conducted on a single cell of a full-scale air-cooled heat exchanger at the Crockett Co-Generation Plant located in Crockett, California, USA. The site is located

on the south shore of the San Francisco Bay at the Carquinez Straits, approximately *25* miles north-northeast of San Francisco.
The plant, which began operation in 1996 is a 240 MWe gas-fired, combined-cycle unit (GE, STAG 107FA), equipped with a 160 MW gas turbine (GE, Model 7FA), a heat recovery steam generator (HRSG) (Henry Vogt Co,) and an 80 MW steam turbine. The turbines are connected to the generator on a single shaft. The plant supplies electricity to the grid and provides process steam (nominally 250,000 lb/hr @ 450 psi) to the C&H Sugar Company's refining plant located on a neighboring site.

The site meteorology is favorable to dry cooling. The temperature is normally cool at an annual average of about 65F. There are, however, three to four hundred hours per year at 80F or above giving ample opportunity to benefit from the use of enhancement methods.

Test set-up

The layout of the air-cooled condenser and exchanger are shown in Figure 1. The test cell is identified as ACE B. Spray nozzles were mounted on a movable spray rack which was hung below the fan. They are shown in operation in Figure 2.

Measurements were made of inlet air dry bulb and wet bulb temperatures both below and above the fan, air exit temperatures on the outside of the finned tube bundles, the spray pressure and flow rate, heat exchanger process side flow rate and inlet and exit temperatures and ambient wind speed and direction.

Test results

Figure 3 shows the test results for a typical day of operation.

The following observations are noteworthy.

- The sprays were turned on at 1:15 pm and off at 3:25 pm.
- The average dry bulb temperature rises from 70 F at noon to 80 F at about 2:15 pm and then remains nearly constant until 3:45 pm. (The spike to 85 F at 3:20 pm is an result of a burst hose spraying hot water on the North sensor and can be ignored.)
- The average inlet wet bulb rose uniformly over the entire test period from 60 F at noon to 64 F at 3:45 pm.
- As a result, the wet bulb depression increases from 10 F at noon to 17 F at 2:15 pm and then decreases to 16 F at 3:45 pm.
- After the sprays were turned on at 1:15 pm the cooling effect rose from 6 F at 1:15 pm to 10 F at 2:15 and then leveled off, as displayed in Figure 4.

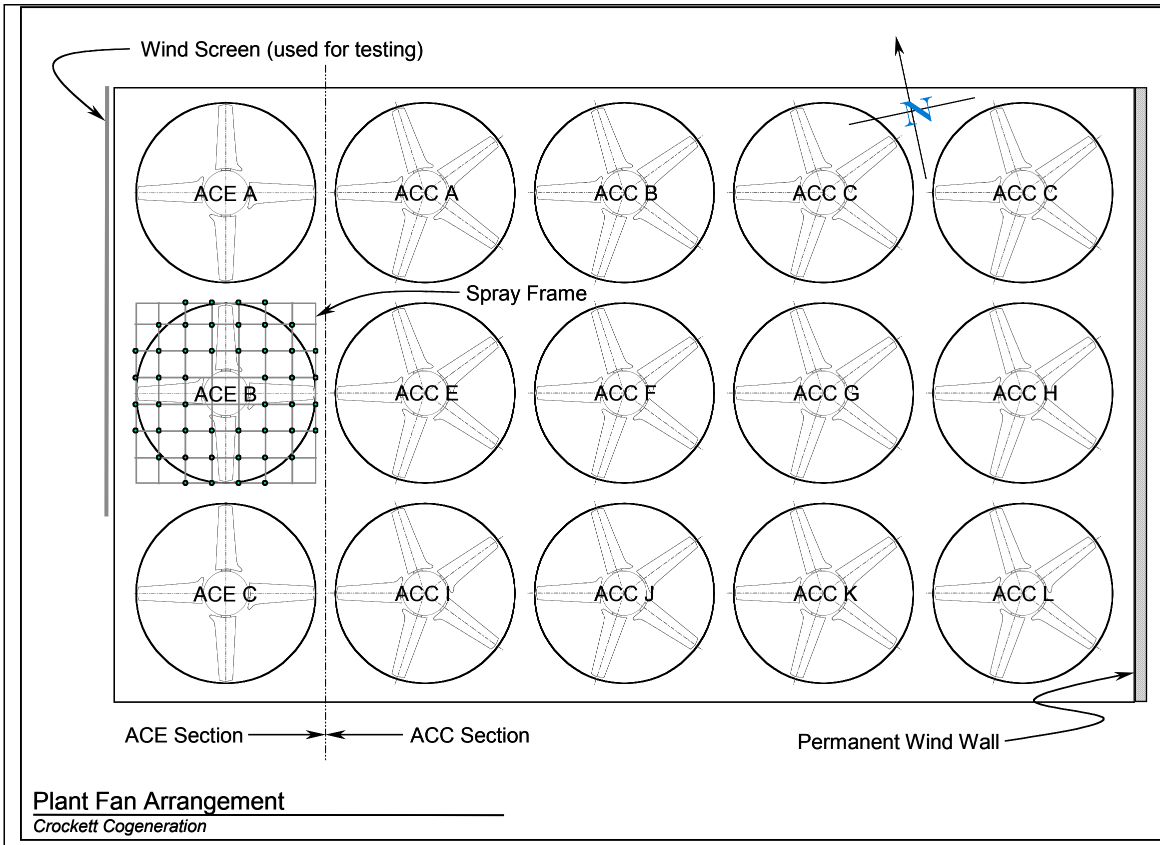

Figure 1
ACC/ACE Layout

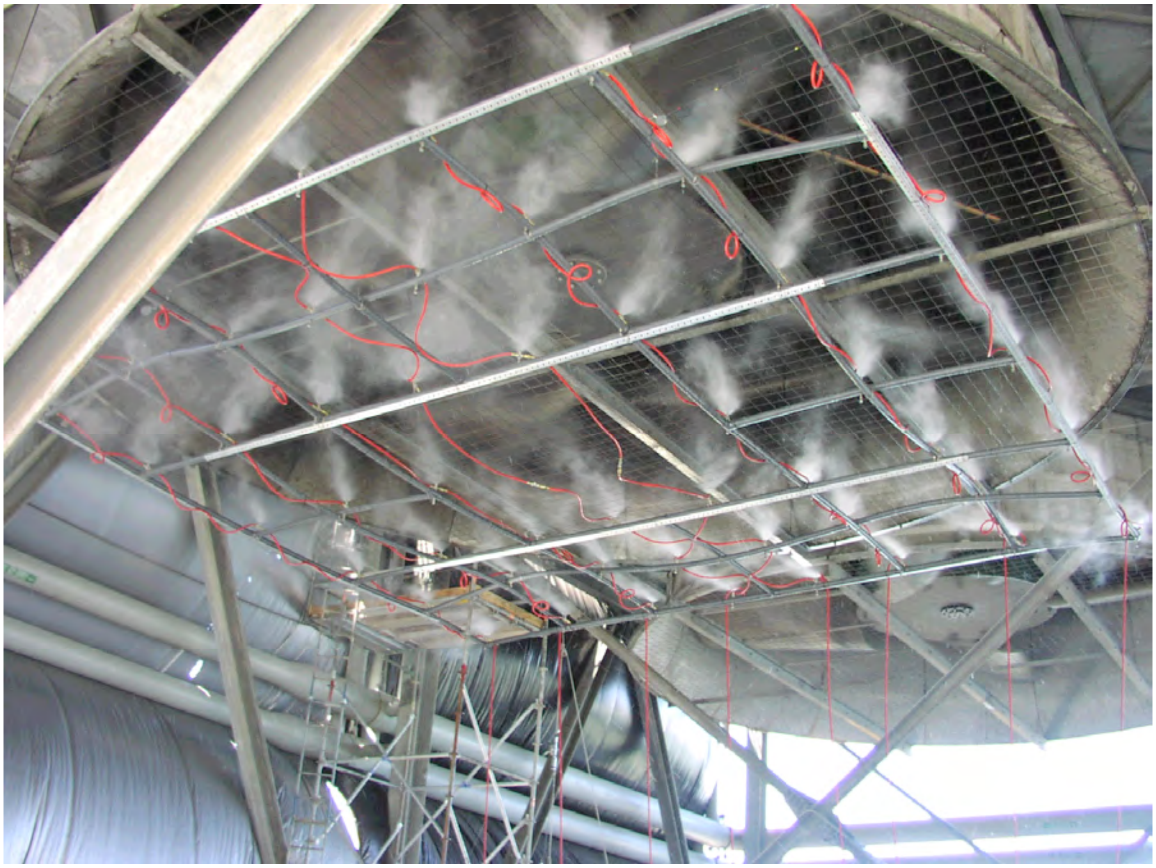

Figure 2
Sprays in Operation under Cell ACE-B

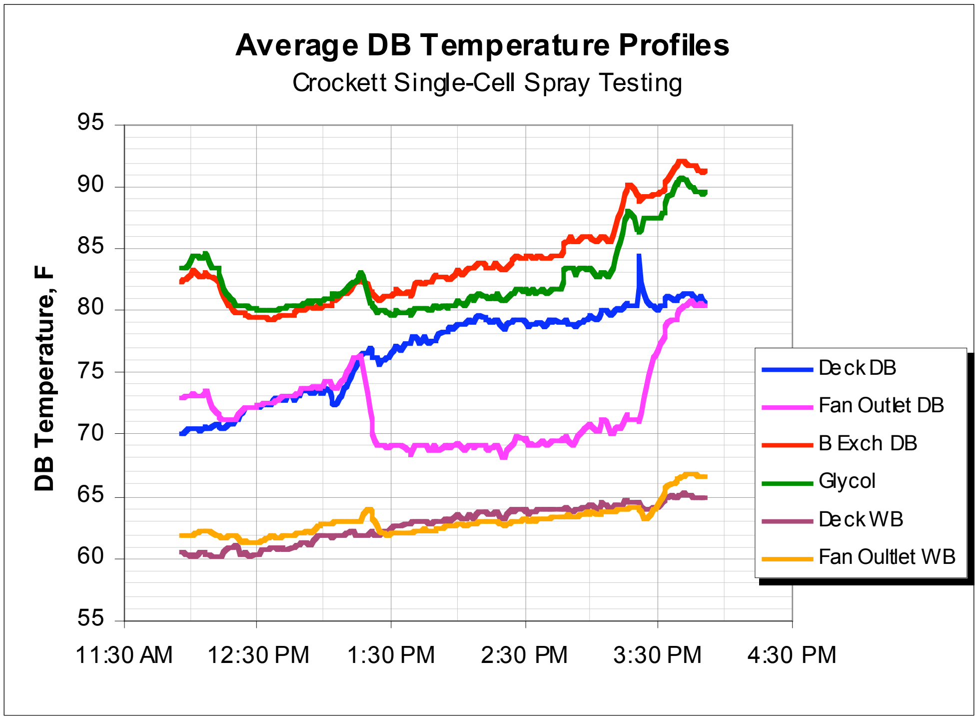

Figure 3
Typical Test Results

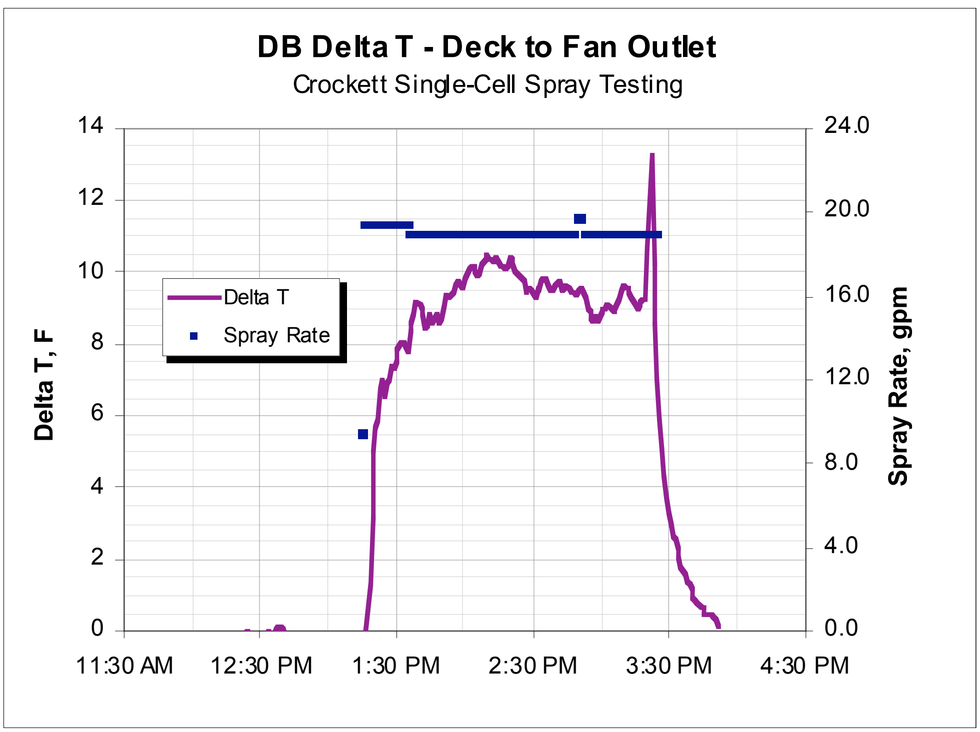

Figure 4
Cooling Effect During Spray Period

On the basis of test results taken over the eight week testing period, the major variables which determine the cooling effect are the spray flow rate and the meteorological conditions. Secondary variables are droplet size distribution (determined by nozzle type) and residence time (determined by nozzle elevation in these tests). For generalized evaluation purposes, a correlation of cooling effect with the major variables was developed. Figure 5 displays an empirical, dimensional correlation between the cooling effect and the product of the wet bulb depression (in deg F) and the spray rate (in gpm).

The evaporation of droplets in an air stream is driven by the normal mass transfer mechanisms---the vapor pressure of the water at the droplet surface, the partial pressure of water vapor in the atmosphere, and the surface area of the droplets in the spray. To a first approximation, the surface area is proportional to the spray flow rate (for similar droplet size distributions) and the driving force is closely related to the wet bulb depression. The agreement is quite good with most of the data over a wide range of operating conditions falling within +/- 10 to 15% of a best fit line.

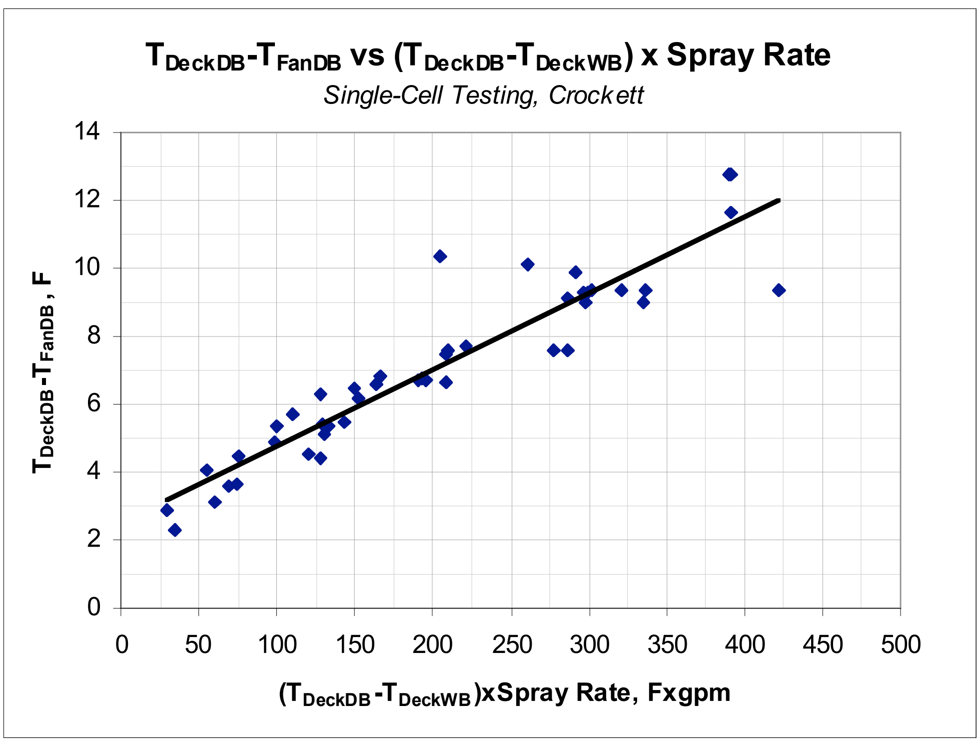

Figure 5
Correlation of Cooling Effect Results

This correlation will be used later to evaluate the performance of the full scale spray enhancement system,

Flow visualization

Preliminary estimates of the cooling effect required suggested that a spray rate of approximately 12 gpm per cell would suffice. Additionally, it was determined that the nozzles would be mounted on the fan bridge inside the cells in order to simplify the installation. It remained to determine where to locate the nozzles and how to orient them in order to maximize the fraction of the sprayed liquid that would evaporate in the air stream and to minimize the amount of unevaporated liquid impinging on the finned tube surfaces.

Using a handheld spray wand, a 2.6 gpm spray stream was sprayed into the inlet air from several locations along the fan bridge above the fan in Cell ACC-I (See Figure 1). Figure 6 shows the spray wand and Figure 7 indicates the several locations from which spraying was done.

Figure 6
Spray Wand for Flow Visualization

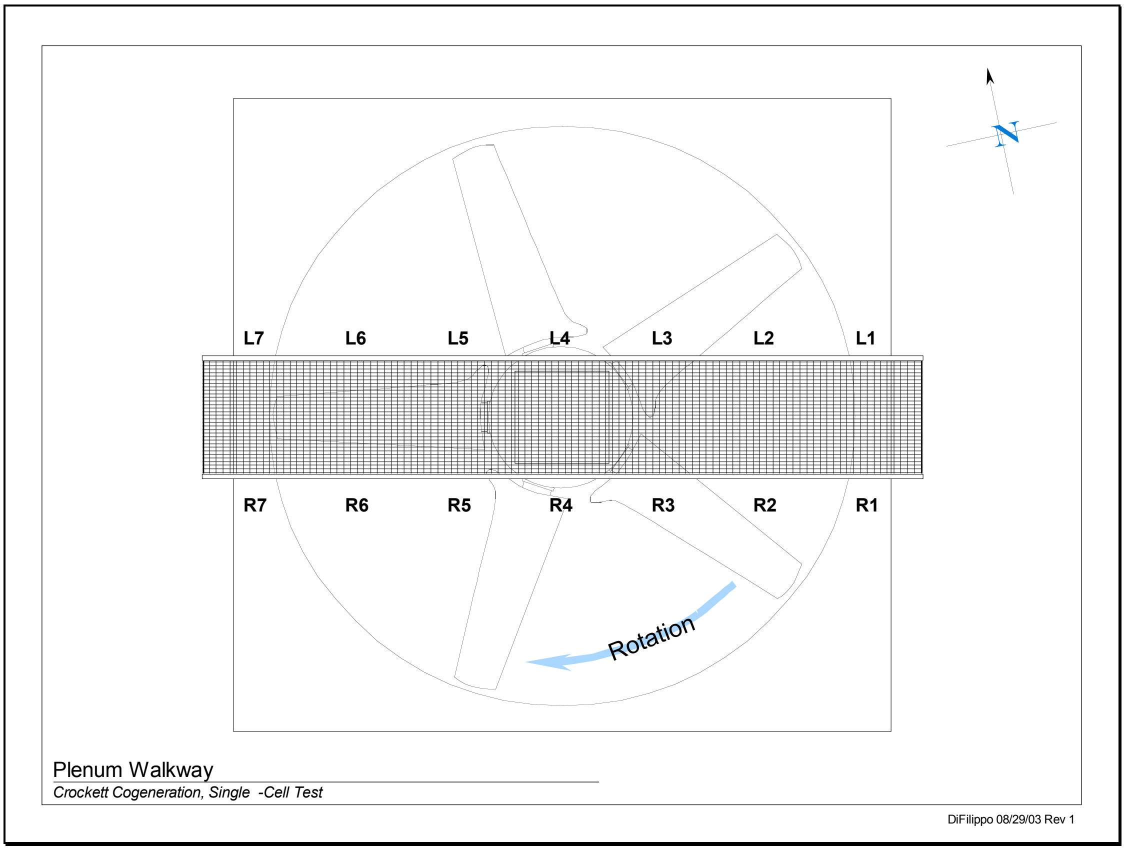

Figure 7
Location of Spray Points on Fan Bridge

The spray lance was typically held at the height of the catwalk top rail (approximately 3 ½ feet above the catwalk floor level and could be pointed in different directions (up, down, or horizontally and at different angles relative to the catwalk). In a few instances, the lance was lowered to the catwalk floor level or held to a level of 8 to 10 feet above the catwalk floor.

Figure 8 provides a sketch of the general airflow pattern inside the cell. The fan rotates in a clock-wise direction (looking down from the top) and imparts a general swirl flow to the air passing through the cell. The flow is highly unsteady and is generally ordered as follows:

- in the lower part of the cell the flow rotates in a toroidal pattern with a secondary (also clockwise looking in the direction of the primary swirl) rotation; (See Figure 9)

– in the upper part of the cell (above the cross structural members) the flow is primarily upward and turns outward toward the upper portion of the tube bundles.

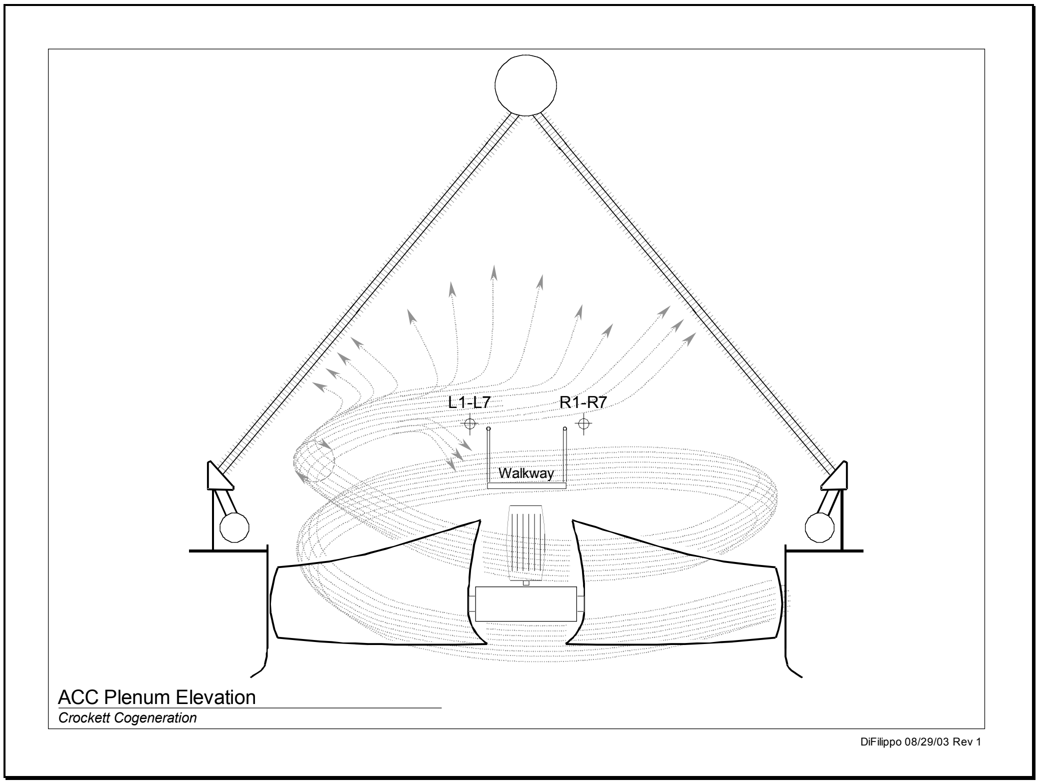

Figure 8
Inferred Flow Pattern Inside Cell

Figure 9
Spray Entrainment in Clockwise Swirl Flow in Lower Part of Cell

Injection at 2.6 gpm at several locations and in differing angles relative to the horizontal and to the catwalk confirmed the existence of the clock-wise toroidal circulation (See Figures 10 and 11). This flow pattern can be exploited to obtain both longer residence times for spray droplets and to minimize the amount of unevaporated liquid impinging on the finned tube bundles.

Corner Injection

At location L1 and R7, spray introduced into the airflow outboard of the fan circumference turns immediately upward and is not entrained in the clockwise circulating flow pattern characteristic of the lower portion of the cell (See Figure 12). Therefore, spray at that location gives improved coverage of bundle areas in the northeast (L1) and southwest (R7) corners particularly in the upper portion of the cell.

Figure 10
Toroidal Flow Pattern---Downflow at Hub

Figure 11
Toroidal Flow Pattern---Down Near Hub; Up Near Bundles

Figure 12
Upflow in Northeast Corner (Location L-1)

Recommendation

In order to provide a spray rate of 12 gpm in a single cell, the recommended arrangement is the following:

1. Two spray nozzles of approximately 5 gpm each should be located at the L-6 and R-2 positions at a level near the top of the catwalk railing. Nozzles of the hollow cone type with cone angles of 60 to 90° directed horizontally at a 45 to 60° angle from the perpendicular to the catwalk in the direction of the primary, clockwise swirl.
2. Two nozzles with capacities of approximately 1 gpm each should be located at the L-1 and R-7 positions at a level near the top of the catwalk railing. These nozzles, also of the hollow cone type with cone angle of 60 to 90°, should be directed vertically.

Full Scale Operation

In the Spring , 2004, the full-scale spray system was installed at Crockett. Two 5.5 gpm nozzles and two 1.1 gpm nozzles were installed in each of the 12 cells for a total spray flow of 13.2 gpm per cell. On August 27, 2004, temperatures rose to over 90 F, and the steam turbine backpressure rose to 6 in Hga. The sprays were turned on from 14:55 to 16:46.

Figures 13 through 15 show the ambient and operating conditions during that day. Since both the ambient air temperature and the steam flow were changing continuously and erratically, it is difficult to discern the effect of spraying on the backpressure from a simple plot of backpressure vs. time as displayed in Figure 15.

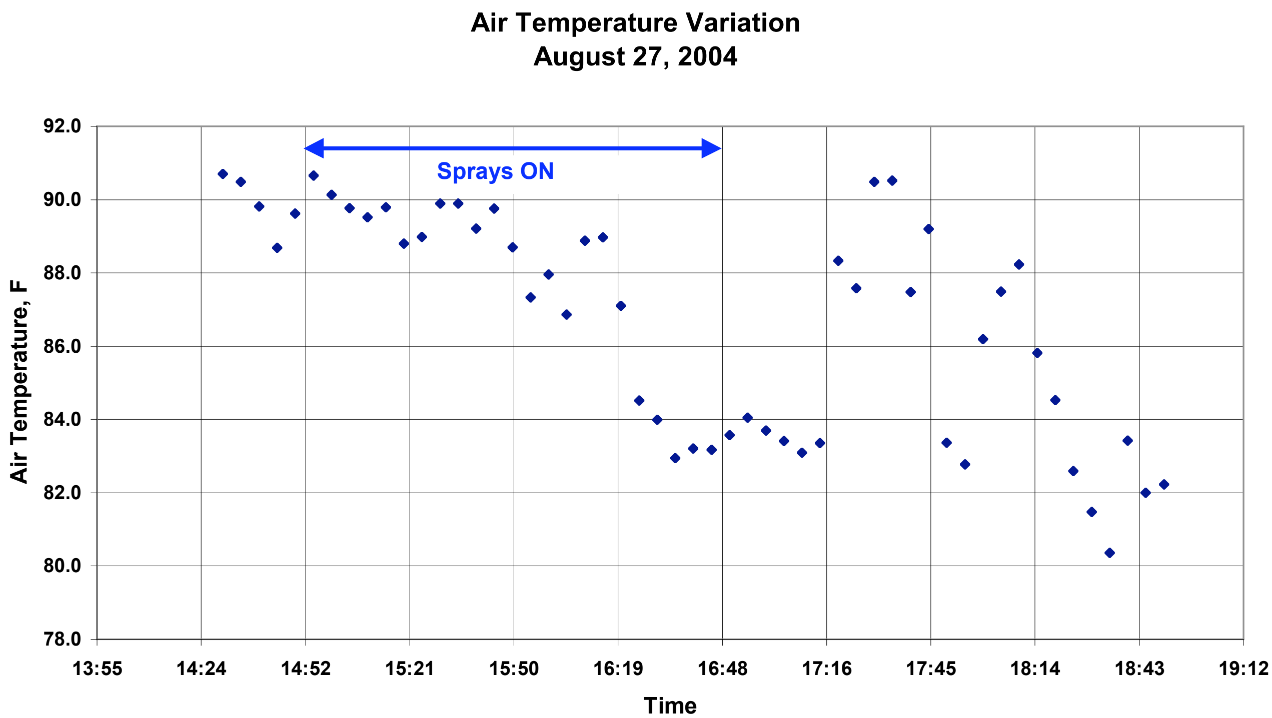

Figure 13

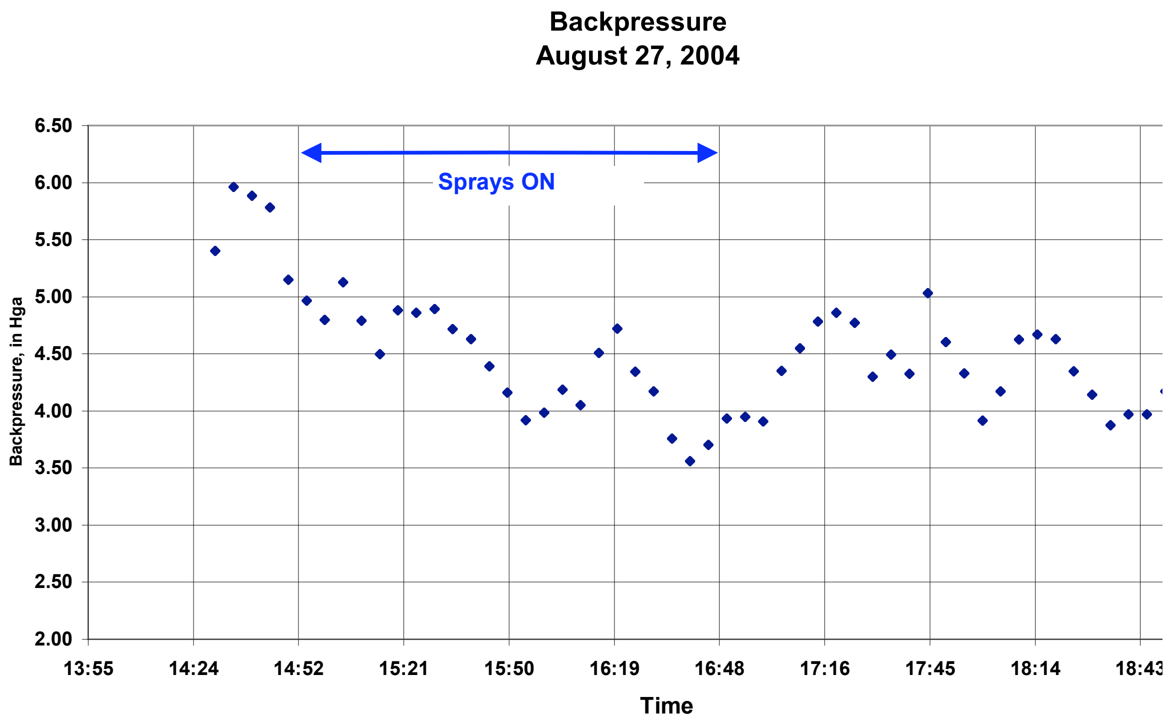

Figure 14

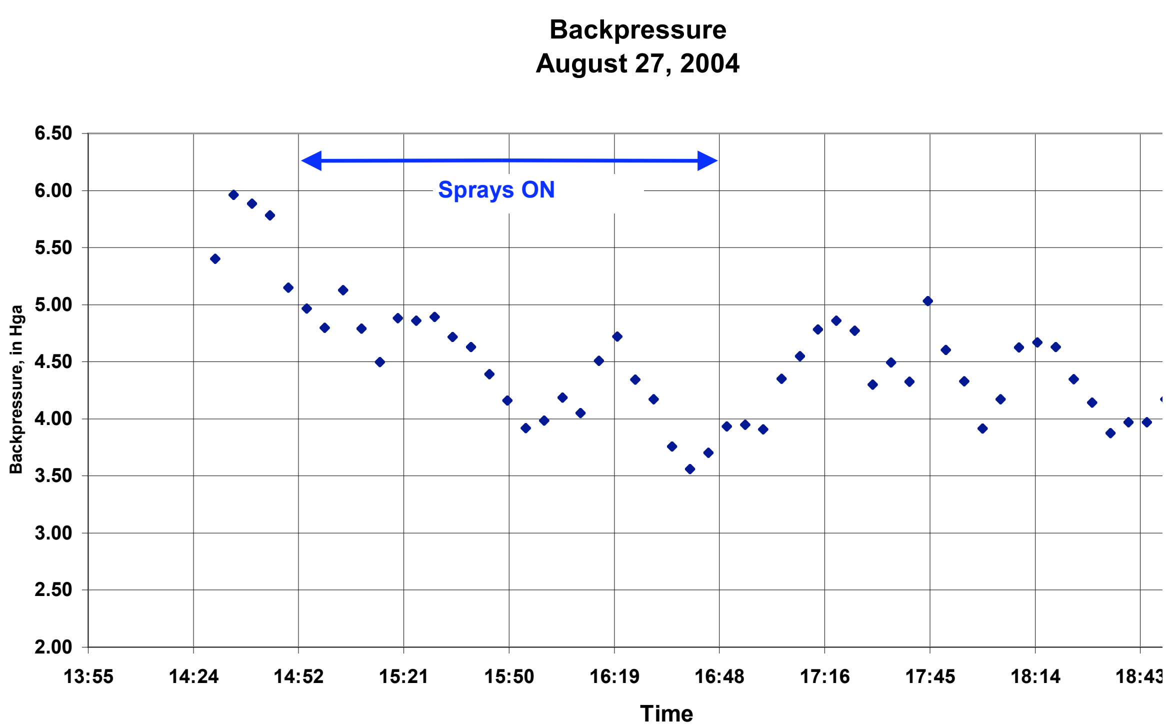
Backpressure
August 27, 2004
Sprays ON
Backpressure, in Hga
6.50
6.00
5.50
5.00
4.50
4.00
3.50
3.00
2.50
2.00
13:55
14:24
14:52
15:21
15:50
16:19
16:48
17:16
17:45
18:14
18:43
Time

Figure 15

Figures 16 and 17 display backpressure vs. steam flow for narrow ranges of ambient temperature both with (Figure 17) and without (Figure 16) sprays in operation. The original performance curves as provided by Balcke-Dürr are also plotted for ambient temperatures of 80 F and 90 F which bracket the day's ambient temperatures. Several points are noteworthy.

1. The performance without spray (Figure 16) is consistently better than the vendor-supplied performance curves. This may be due to several factors.
    a. The plant ambient temperature measurement may not be representative of the actual, average inlet air temperature.
    b. The airflow to the ACC may be higher than the design flow if, for example, the fans were pitched to an angle other than the design pitch.
    c. The steam turbine exit quality may be lower than assumed in the design case.

    None of these possibilities could be confirmed.
2. There is considerable scatter in the data. Points in a narrow temperature range vary around a best fit line by more than +/-0.25 in Hga. This scatter is comparable to the apparent improvement in performance with the sprays and makes a direct comparison of nominally identical conditions with and without sprays difficult. Experience with longer term tests in 2001 suggests that the apparent scatter is likely due to continuous, erratic variations in wind speed and direction which was not monitored on August 27 nor could it have been easily corrected for.
3. The "cluster" of points with spray in Figure 17 appears to be generally lower in backpressure than those without spray by approximately 0.25 to 0.5 in Hga.

A clearer indication of the effect of sprays in shown in Figure 18. For points taken throughout the day, a value of heat duty (represented by steam flow) divided by ITD (defined as the condensing temperature corresponding to the turbine backpressure minus the ambient air temperature) is plotted for several hours including time periods with and without spraying.

When the sprays are turned on, the air temperature entering the ACC is reduced with a corresponding reduction in the backpressure and the condensing temperature. The ambient temperature measurement is unaffected. Therefore, the calculated ITD decreases and the ratio, Q/ITD, increases. This is clearly seen in Figure 18 during the period with the sprays on. It also appears that the performance is steadier and exhibits less scatter during the "spray on" period. We have no explanation for this observation.

Quantitatively, the change in backpressure with spraying is in approximate agreement with what would be predicted from the 2001 test results. The correlation shown in Figure

5 for data taken on the ACE (not the ACC) would predict a cooling effect of approximately 7 F. Correcting this for the difference in air flows between the two cells gives an expected cooling effect of 6.3 F corresponding to a backpressure reduction of about 0.5 in Hga and an ITD decrease of about 12 to 15%. These values are reasonably consistent with the data shown on Figures 16 though 18 for the full-scale performance in August, 2004.

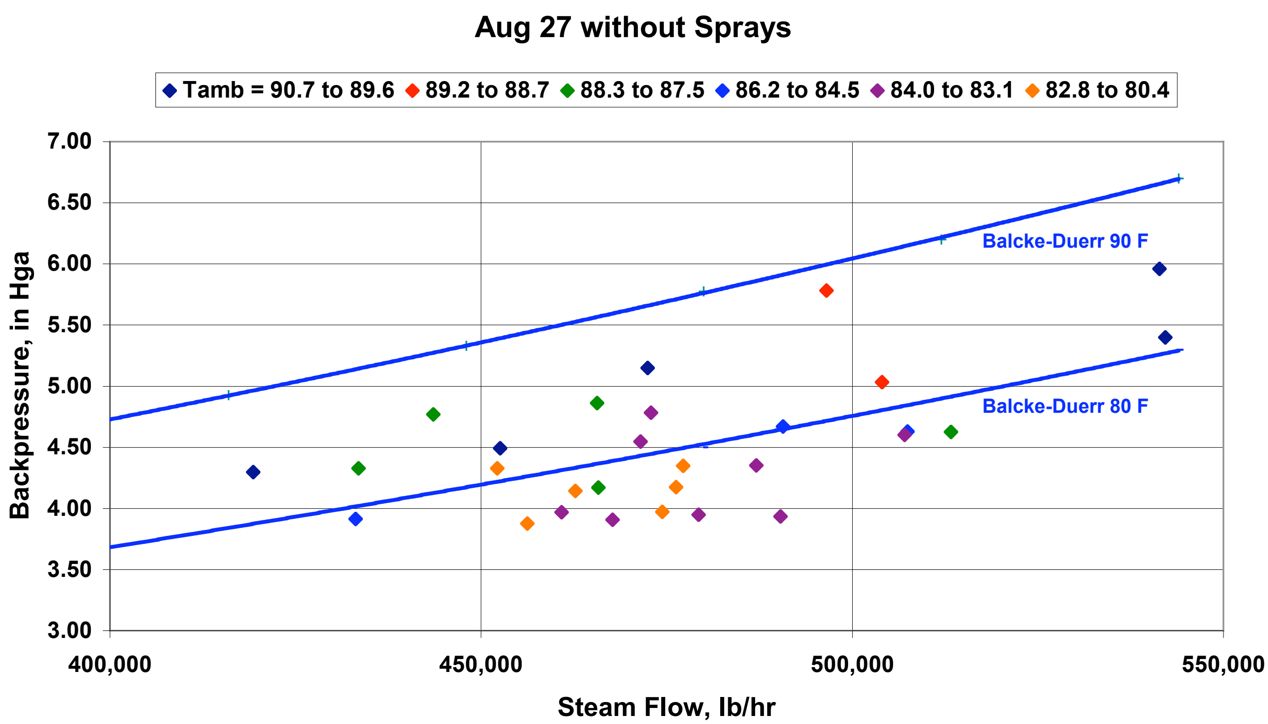

Figure 16

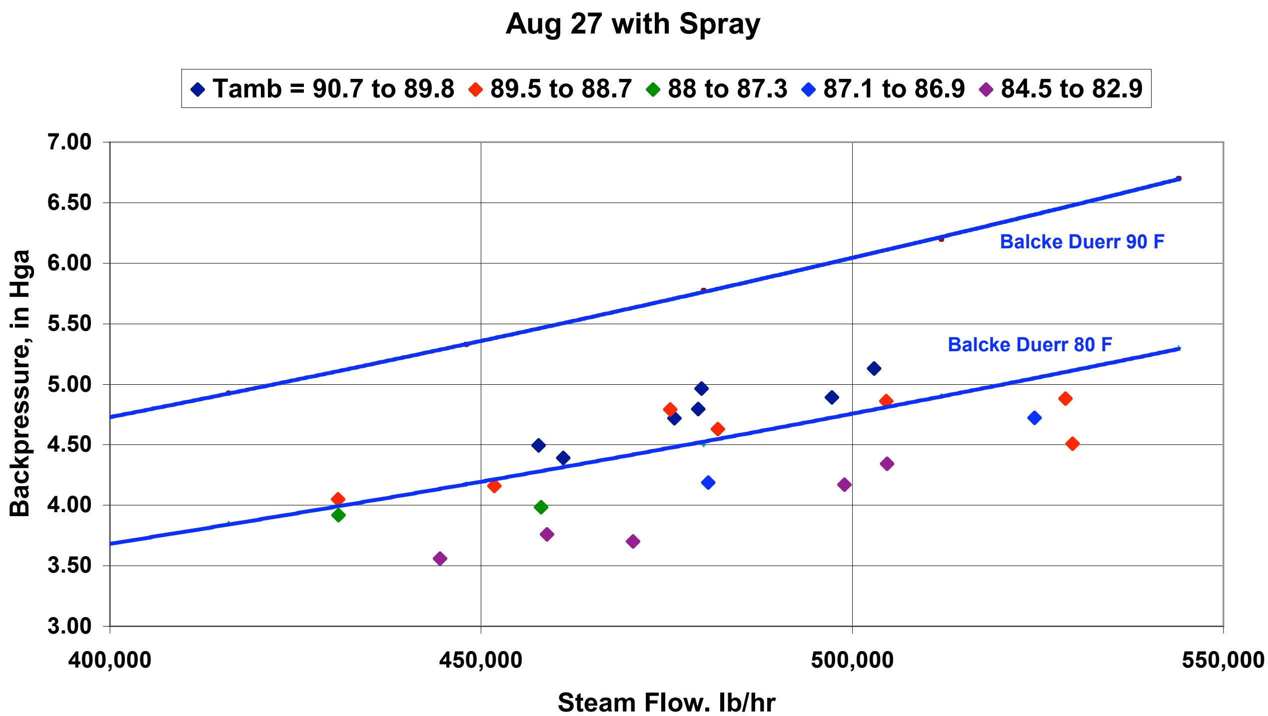
Aug 27 with Spray
Tamb = 90.7 to 89.8
89.5 to 88.7
88 to 87.3
87.1 to 86.9
84.5 to 82.9
Balcke Duerr 90 F
Balcke Duerr 80 F
7.00
6.50
6.00
5.50
5.00
4.50
4.00
3.50
3.00
Backpressure, in Hga
400,000
450,000
500,000
550,000
Steam Flow. lb/hr

Figure 17

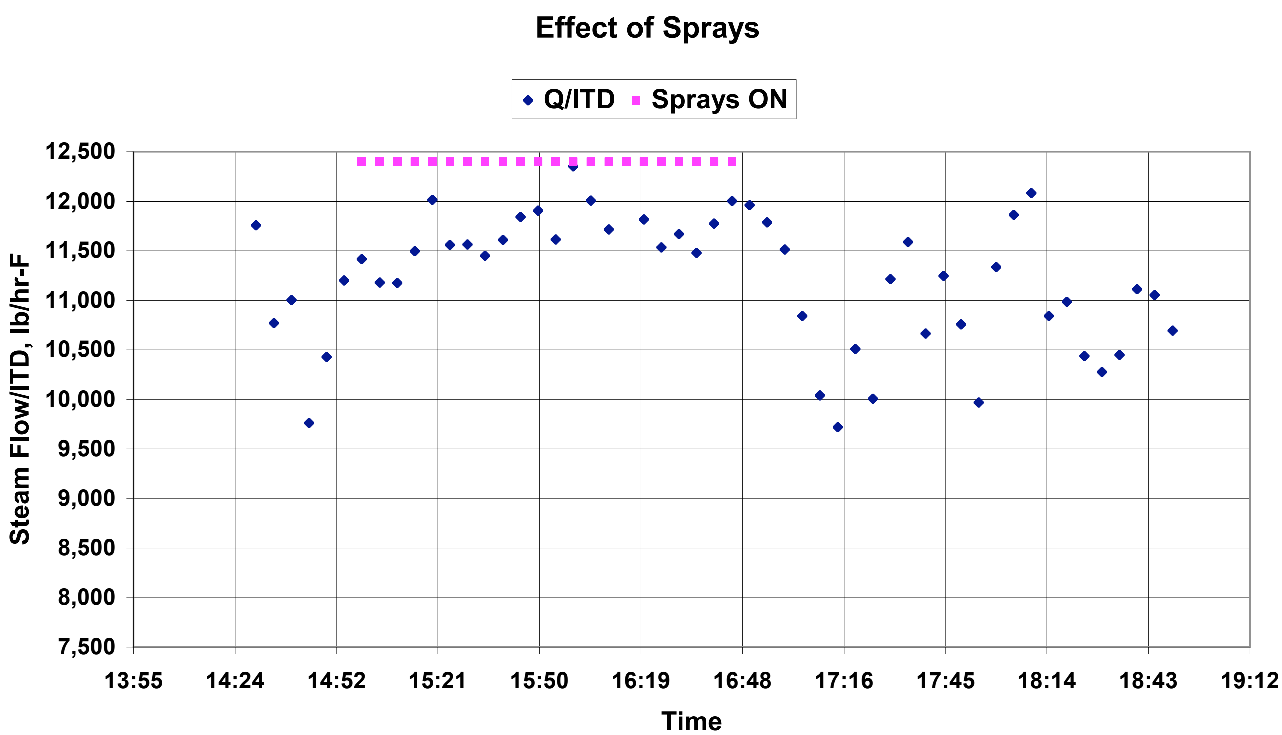
Effect of Sprays
Q/ITD
Sprays ON
12,500
12,000
11,500
11,000
10,500
10,000
9,500
9,000
8,500
8,000
7,500
Steam Flow/ITD, lb/hr-F
13:55
14:24
14:52
15:21
15:50
16:19
16:48
17:16
17:45
18:14
18:43
19:12
Time

Figure 18

Conclusions

- Spray tests conducted on a single cell of the air-cooled heat exchanger at Crockett Co-Generation demonstrated a cooling effect that correlated well with the product of spray rate times wet bulb depression.
- Flow visualization tests showed that spraying inside the air-cooled condenser cells could provide adequate residence time by injecting the spray into the vortical flow region just above the fan. This minimized the wetting of the finned tube surfaces.
- The expected improvement in performance and reduction turbine exhaust pressure was realized during one day of full-scale spray operation in August, 2004.

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Maulbetsch, J. S. and M. N. DiFilippo, Spray Cooling Enhancement of Air-Cooled Condensers, Presented at XIIth Conference on Cooling Towers, International Association for Hydraulic Research, Sydney, Australia, November 12 – 15, 2001.

Maulbetsch, J. S., M. N. DiFilippo, K. D. Zammit, J. O'Hagan and M. Layton, Spray Cooling—An Approach to Performance Enhancement of Air-Cooled Condensers, Proceedings of EPRI Cooling Tower Technology Conference, Charleston, SC, EPRI Report No. 1004119, August, 2003